Nonrelativistic QCD and X(3872)

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1. NRQCD and Heavy Quarkonium

Nonrelativistic hadron system

Separate scales m, mv, mv2, Λ_{QCD} with v2<<1□ □1

Effective theory, Factorization of short- distance and long-distance parts

Experimental challenges from LHC data

How to understand production and decay

Important test ground for QCD and hadron physics

2. New hadron states—XYZ

X(3872), Y(4260), Z(4430),…Z(3900), Z(4020),…

What is the nature of XYZ: Hadronic molecules, 4-quark states, Hybrids, threshold effects?

What is the relation of XYZ to conventional quarkonia?

Interpretations of X(3872) and Its Production at Hadron Colliders

Kuang-Ta Chao   Peking University

In Collaboration with C. Meng & H. Han

Outline

- Mini review of X(3872)
- X production at hadron colliders
- X decays to $J/\psi\gamma$ and $\psi(2S)\gamma$
- X production in B meson decays
- Summary

Experimental information

- 1st observed by Belle Collaboration in

  $B \to J/\psi\pi^+\pi^- K$ Belle'03

- Mass, width and quantum numbers:

• $m_X = 3871.68 \pm 0.17$ MeV PDG'12

$m_X - m_{D^0 D^{*0}} = -0.142 \pm 0.220$ MeV Tomaradze *et al.*'12

• $\Gamma < 1.2$ MeV CL $= 90\%$ PDG'12

• $J^{PC} = 1^{++}$ or 2^{-+}

✓ $J^{PC} = 2^{-+}$ is favored by the $\omega \to \pi^+\pi^-\pi^0$ mass spectrum in $B \to X(3872)K \to J/\psi\omega(\pi^+\pi^-\pi^0)K$ [BaBar'10], but is excluded by the recent analysis on the angular correlations in $B \to X(3872)K \to J/\psi\rho(\pi^+\pi^-)K$ by LHCb [arXiv:1302.6269]

Experimental information

- Decay pattern:
- Well-established decay modes:

  $J/\psi\rho(\pi^+\pi^-), J/\psi\omega(\pi^+\pi^-\pi^0), D^0\bar{D}^{*0}/\bar{D}^0D^{*0}/D\bar{D}\pi, J/\psi\gamma$

  Relative ratios of these 4 modes: 1: 1: 10: 0.3 PDG'12

  ✓ Large isospin violations

  $$\mathrm{R}_{\rho/\omega} = \mathrm{Br}(X \to J/\psi\rho)/\mathrm{Br}(X \to J/\psi\omega) \approx 1$$

  ✓ $\mathrm{Br}(X \to J/\psi\rho) = \mathrm{Br}(X \to J/\psi\pi^+\pi^-) \equiv \mathrm{Br}_0 < 9\%$

- B-production:

  $1 \times 10^{-4} < \mathrm{Br}(B \to X(3872)K) < 3.2 \times 10^{-4}$ BaBar'05

  $\mathrm{Br}(B \to X(3872)K)\mathrm{Br}_0 = (8.6 \pm 0.8) \times 10^{-6}$ PDG'12

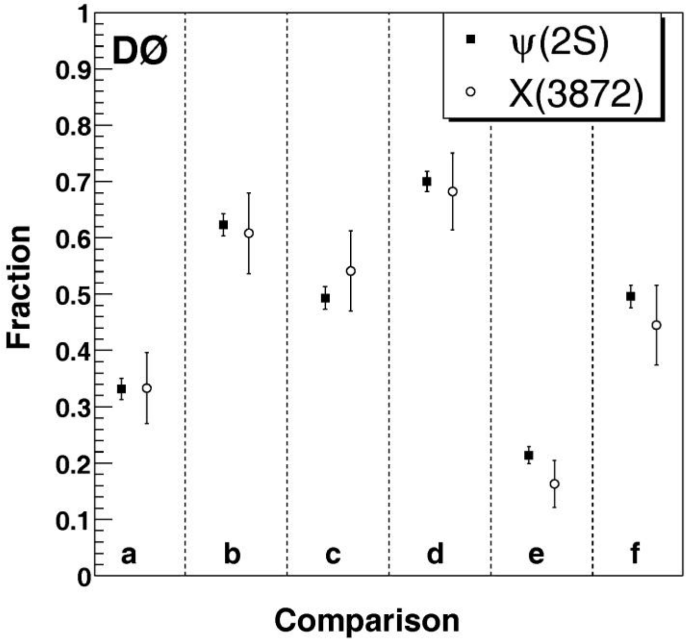
  $$2.6\% < \mathrm{Br}_0 < 9\%$$

Experimental information

- ➢ Hadro-production
- Large production rate: $\frac{\sigma(p\bar{p}\to X)\mathrm{Br}_0}{\sigma(p\bar{p}\to\psi\prime)}\frac{\epsilon_{\psi\prime}}{\epsilon_X} = (4.8 \pm 0.8)\%$ CDF'04
- Similar behaviors to ψ' production in p_T distribution and …

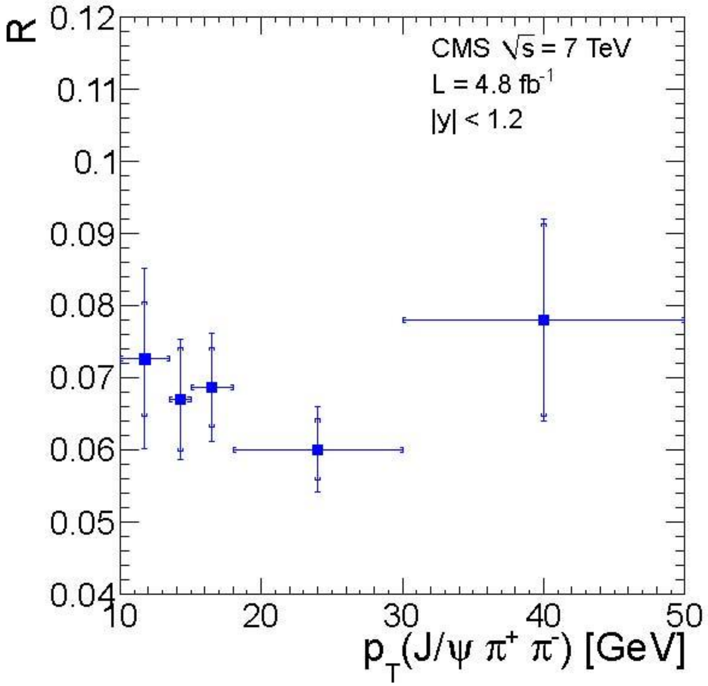
D0 PRL'04

a. $p_T > 15$ GeV b. …



CMS arXiv:1302.3968

Ratio to ψ' is not depend on p_T



$D^0\bar{D}^{*0}$ molecule models

[Tornqvist'04, Voloshin'04, Swanson'04, Braaten'04, …]

- X(3872) is a loosely bound state of $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$
- The mass, quantum numbers and the large isospin violation can be understood naturally.
- The large production rate seems to be questionable
- ✓ Naively, $\sigma(X) \sim k_0^3$, where the relative momentum of $D^0\bar{D}^{*0}$ in the bound state $k_0 = \sqrt{2\mu_{DD^*}|E_b|} < 40$ MeV
- ✓ Explicit calculations [Bignamini *et al*, PRL'09]:

  $\sigma_{\text{CDF}}^{\text{th}}(X) < 0.085\ \text{nb} \quad v.s. \quad \sigma_{\text{CDF}}^{\text{ex}}(X)\text{Br}_0 = 3.1 \pm 0.7\ \text{nb}$
- ✓ Artoisenet and Braaten [PRD'10] proposed that rescattering effects of $D^0\bar{D}^{*0}$ may enhance the rate to values consistent with the CDF data if the upper bound of the relative momentum of $D^0\bar{D}^{*0}$ in rescattering is as large as $3m_\pi \approx 400$ MeV

$\chi'_{c1} - D^0\bar{D}^{*0}$ mixing model

Meng, Gao and Chao, hep-ph/0506222, PRD87(2013)074035

- $X(3872)$ is a mixed state of χ'_{c1} and $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$ continuum
- Both the two components are substantial, and they may play different roles in the dynamics of $X(3872)$.

1. The short distance (the b- and $hadro$-) production and the quark annihilation decays of $X(3872)$ proceed dominantly through the χ'_{c1} component.
2. The $D^0\bar{D}^{*0}$ component is mainly in charge of the hadronic decays of $X(3872)$ into $DD\pi/DD\gamma$ as well as $J/\psi\rho$ and $J/\psi\omega$.
3. The long distance coupled-channel effects between the two components could renormalize the short distance dynamics by a product factor $Z_{c\bar{c}}$, the equivalent probability of χ'_{c1} in $X(3872)$.

$\chi'_{c1} - D^0\bar{D}^{*0}$ mixing model

- B production rate: Meng, Gao and Chao'05

$$\frac{\mathrm{Br}(B\to\chi'_{c1}K)}{\mathrm{Br}(B\to\chi_{c1}K)} = 0.75\text{–}1$$

$$\mathrm{Br}(B\to\chi'_{c1}K) = (2\text{–}4)\times 10^{-4}$$

- Rescattering of the $D^0\bar{D}^{*0}$ and $D^+\bar{D}^{*-}$ $(virtual)$components:

Meng and Chao, PRD'07

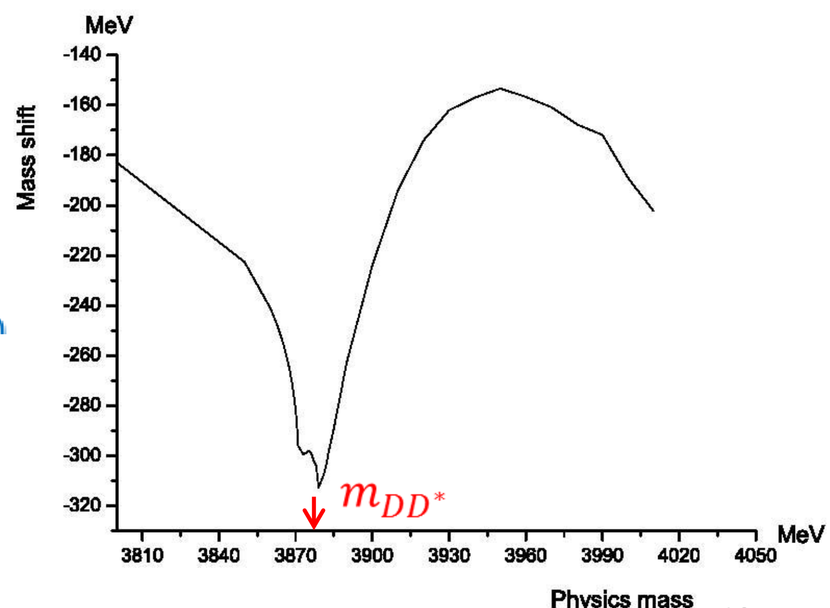
$$\frac{\mathrm{Br}(X\to J/\psi\rho)}{\mathrm{Br}(X\to J/\psi\omega)} = 0.9\text{–}1.2$$

- Mass problem:

Coupled-channel models

Li & Meng & Chao'09; Danilkin & Simonov'10

The sharp mass shift curve induced by the S-wave coupling lower the "bare" mass of χ'_{c1} towards the $D^0\bar{D}^{*0}$ threshold.



X production at hadron colliders

NRQCD factorization formula

- χ'_{c1} production mechanism in the mixing model:
  [Meng & Han & Chao, arXiv:1304.6710]
  [Similar work was done by Butenschoen & He & Kniehl, arXiv: 1303.3524]

- Energy scales: $m_c \gg m_c v,\ \ m_c v^2, \Lambda_{QCD} \gg E_b$
- Assume X is produced at short-distance via the χ'_{c1} component

$$\sigma\big(pp \to X(J/\psi\pi^+\pi^-)\big) = \sigma(pp \to \chi'_{c1}) \cdot k, \qquad k = Z_{c\bar{c}}\mathrm{Br}_0$$

- Factorization in NRQCD Bodwin & Braaten & Lepage'95

$$d\sigma(pp \to \chi'_{c1}) = \sum_n d\hat{\sigma}\big((c\bar{c})_n\big) \frac{\left\langle O_n^{\chi'_{c1}} \right\rangle}{m_c^{2L_n}}$$

$$= \sum_{i,j,n} \int dx_1 dx_2 G_{i/p} G_{j/p}\, d\hat{\sigma}(ij \to (c\bar{c})_n) \left\langle O_n^{\chi'_{c1}} \right\rangle$$

$n = {}^3P_1^{[1]}$ & ${}^3S_1^{[8]}$ at leading order in v for χ'_{c1} production

NRQCD factorization formula

- Molecule production mechanism in the molecule model:

  Artoisenet & Braaten, PRD'09

$$d\sigma(pp \to X_{D^0\bar{D}^{*0}}) = d\hat{\sigma}\left({}^3S_1^{[1]}\right)\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[1]}}\right\rangle + d\hat{\sigma}\left({}^3S_1^{[8]}\right)\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[8]}}\right\rangle$$

At NLO in α_s: $d\hat{\sigma}\left({}^3S_1^{[1]}\right)/d\hat{\sigma}\left({}^3S_1^{[8]}\right) \approx 5.3 \times 10^{-4}$ for CDF widow, thus [Meng & Han & Chao, arXiv:1304.6710]

$$d\sigma(pp \to X_{D^0\bar{D}^{*0}}) = d\hat{\sigma}\left({}^3S_1^{[8]}\right)\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[8]}}\right\rangle$$

- ✓ The two models are different in combinations of the $c\bar{c}$ channels in the factorization formula, leading to different CMS pT distributions.
- ✓ The χ'_{c1} production is similar to χ_{c1}, and therefore large production rate is expected (like ψ(2S) and J/ψ).

NRQCD factorization formula

- NLO calculations:
- We choose $\mu_r = \mu_f = m_T = \sqrt{p_T^2 + 4m_c^2}, \mu_{NR} = m_c = 1.5 \pm 0.1$ GeV, and vary $\mu_{r,f}$ from $m_T/2$ to m_T to estimate the errors.
- The other details can be found in Ma & Wang & Chao'11 (MWC'11)
- To compare our following results with the available ones for χ_{c1} production [MWC'11], we parameterize the matrix elements as
- $\left\langle O_{^3P_1^{[1]}}^{\chi'_{c1}} \right\rangle = \left\langle O_{^3P_1^{[1]}}^{\chi_{c1}} \right\rangle = \frac{9}{4\pi}|R'_{1P}(0)|^2, |R'_{1P}(0)|^2 = 0.075\ \mathrm{GeV}^5$
- $r = m_c^2 \left\langle O_{^3S_1^{[8]}}^{\chi'_{c1}} \right\rangle / \left\langle O_{^3P_1^{[1]}}^{\chi'_{c1}} \right\rangle$ ($r_{1P} = 0.27 \pm 0.06$, MWC'11)
- The cross section in the χ'_{c1} production mechanism is a simple function of r, k and p_T

Fit to the CMS p_T distribution

$\sqrt{S} = 7$ TeV, $|y| > 1.2$, 10 GeV $< p_T < 30$ GeV

- ➢ χ'_{c1} production mechanism:

$r = 0.26 \pm 0.07$, $k = 0.014 \pm 0.006$

$$\sigma^{\text{fit}}_{\text{CMS}}(p\bar{p} \to X(J/\psi\pi^+\pi^-)) = 1.09^{+0.08}_{-0.12}\ \text{nb}\ \ ((1.06 \pm 0.19\ \text{nb})_{\text{ex}})$$

- The central values correspond $\chi^2/2 = 0.26$
- The value of r_{2P} for χ'_{c1} is almost the same as that for $\chi_{c1}(1P)$:

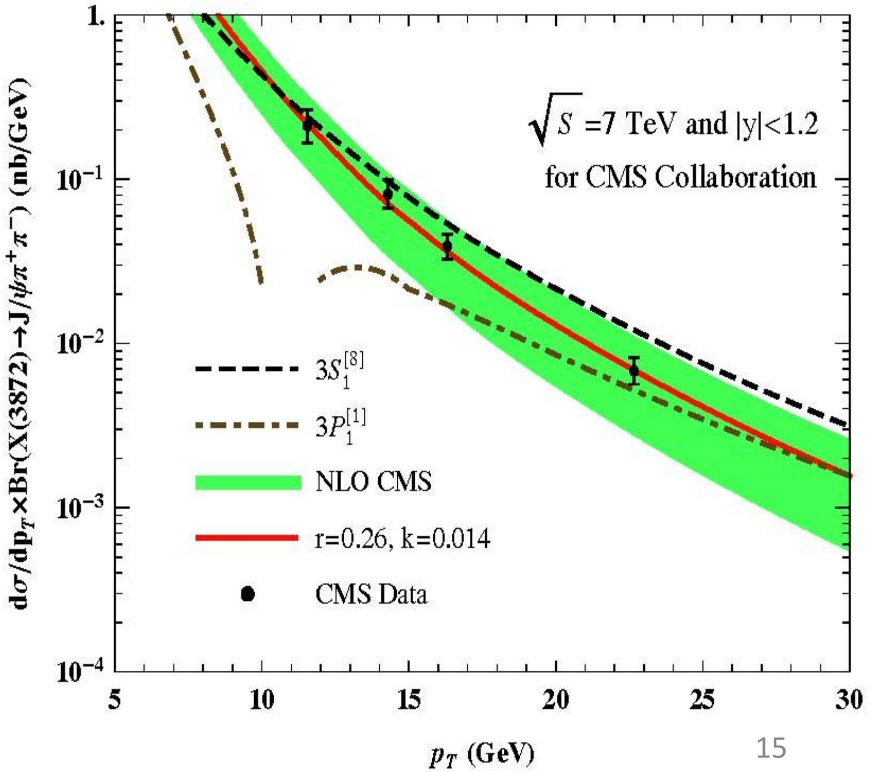
$r_{1P} = 0.27 \pm 0.06$ [MWC'11]

which suggests that X(3872) be produced through its χ'_{c1} component at short distance

- ➢ Molecule production mechanism:

$$\left\langle O^{D^0\bar{D}^{*0}}_{^3S_1^{[8]}} \right\rangle \text{Br}_0 = (6.0 \pm 0.6)10^{-5}\ \text{GeV}^3$$

$\chi^2/3 = 1.03$



Predictions v.s. CDF data

$$\sqrt{S} = 1.96\ \text{TeV}, \qquad |y| > 0.6, \qquad p_T > 5\ \text{GeV}$$

- χ'_{c1} production mechanism:

  Inputs: $r = 0.26,\ k = 0.014$

  $\sigma^{\text{th}}_{\text{CDF}}(p\bar{p} \to X(J/\psi\pi^+\pi^-)) = 2.5 \pm 0.7\ \text{nb}\ \ (v.s.\ (3.1 \pm 0.7\ \text{nb})_{\text{ex}})$

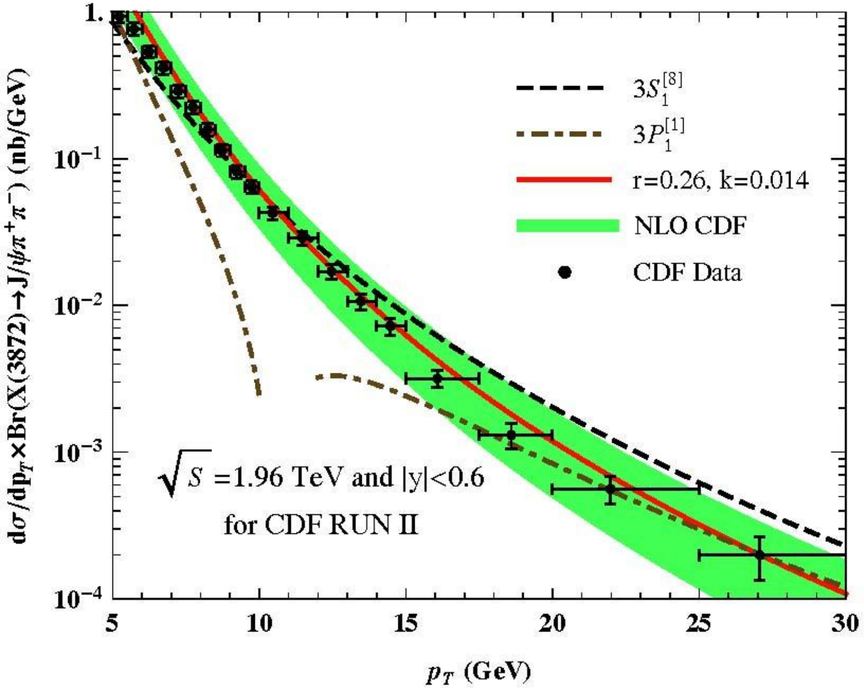
  The predicted p_T distribution of $X(3872)$ is compared with that of ψ' [CDF, PRD'09] (see the diagram)

- Molecule production mechanism:

  $\sigma^{\text{molecule}}_{\text{CDF}} = 1.1 \pm 0.4\ \text{nb}$

  $2.6\,\sigma$ deviation from data

- Both the CMS and the CDF data favor the χ'_{c1} production mechanism, rather than the molecule production mechanism.



Predictions v.s LHCb data

$\sqrt{S} = 7$ TeV, $\quad 2.5 < y < 4.5, \quad 5$ GeV $< p_T < 20$ GeV

- χ'_{c1} production mechanism:

Inputs: $r = 0.26, \quad k = 0.014;$

$$\sigma_{\rm LHCb}^{\rm th-prompt}(p\bar{p} \to X(J/\psi\pi^+\pi^-)) = 9.4 \pm 2.2 \text{ nb}$$

$$v.s. \quad \sigma_{\rm LHCb}^{\rm inclusive} = 5.4 \pm 1.4 \text{ nb}$$ LHCb, PRL'11

- About 20% of data come from non-prompt contributions, thus our prediction is about 2 times larger than the data.
- Both the theoretical and the experimental uncertainties are large.
- More available data are expected to be analyzed.

- Molecule production mechanism:

$$\sigma_{\rm LHCb}^{\rm molecule} = 4.0 \pm 1.3 \text{ nb}$$

Better than ours, but the predicted pT distribution at CMS is less consistent with data.

Single parameter fit

- Fitting k to the CMS data with fixed r

  $(3.1 \pm 0.7\ \mathrm{nb})^{\mathrm{ex}}_{\mathrm{CDF}}$

  $(5.4 \pm 1.4\ \mathrm{nb})^{\mathrm{ex}}_{\mathrm{LHCb}} \cdot 80\%$

- Fitting k to B decay data

r	k	$\chi^2/3$	$\sigma^{\mathrm{th}}_{\mathrm{CDF}}(\mathrm{nb})$	$\sigma^{\mathrm{th}}_{\mathrm{LHCb}}(\mathrm{nb})$
0.20	0.021	0.39	3.26	12.2
0.25	0.015	0.17	2.63	9.87
0.30	0.012	0.20	2.28	8.56
0.35	0.010	0.27	2.06	7.72
0.40	0.008	0.34	1.90	7.14

$$\mathrm{Br}(B \to X(J/\psi\pi^+\pi^-)K) = \mathrm{Br}(B \to \chi'_{c1}K) \cdot k$$

$$= (8.6 \pm 0.8) \times 10^{-6}$$ PDG'12

$$\mathrm{Br}^{\mathrm{fit}}(B \to \chi'_{c1}K) = (3.7\text{–}5.7) \times 10^{-4}$$ Kalashnikova & Nefediev PRD'09

$$\therefore k = Z_{c\bar{c}}\mathrm{Br}_0 = 0.018 \pm 0.004$$

- ✓ Window in the table: $r = 0.20\text{-}0.26$
- ✓ With a modest value $\mathrm{Br}_0 = 5\%$ $\in (2.6\%\text{–}9\%)$

$$Z_{c\bar{c}} = 28\%\text{–}44\%$$

X(3872) decays to ψ(2s)γ and J/ψγ

$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4,$$

BaBar arxiv:0809.0042

Belle arxiv:1105.0177

R < 2.1 (at 90% C.L.)

LHCb arxiv:1404.0275 (NEW)

$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29,$$

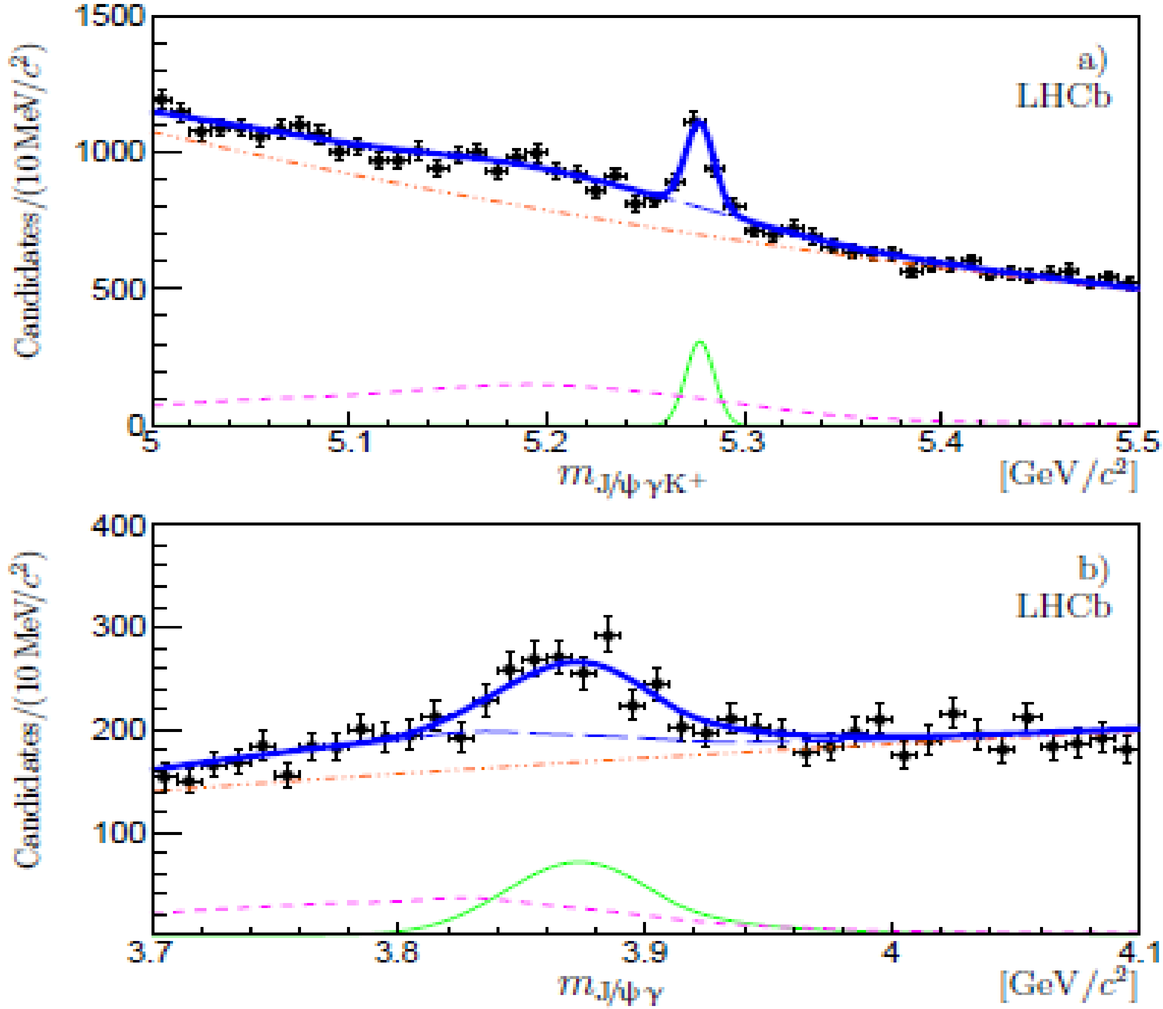


Figure 1: a) Distribution of the $J/\psi\gamma K^+$ invariant mass with fit projection overlaid, restricted to those candidates with $J/\psi\gamma$ invariant mass within $\pm 3\sigma$ from the X(3872) peak position. b) Distribution of the $J/\psi\gamma$ invariant mass with fit projection overlaid, restricted to those candidates with $J/\psi\gamma K^+$ invariant mass within $\pm 3\sigma$ from the B^+ peak position. The total fit (thick solid blue) together with the signal (thin solid green) and background components (dash-dotted orange for the combinatorial, dashed magenta for the peaking component and long dashed blue for their sum) are shown.

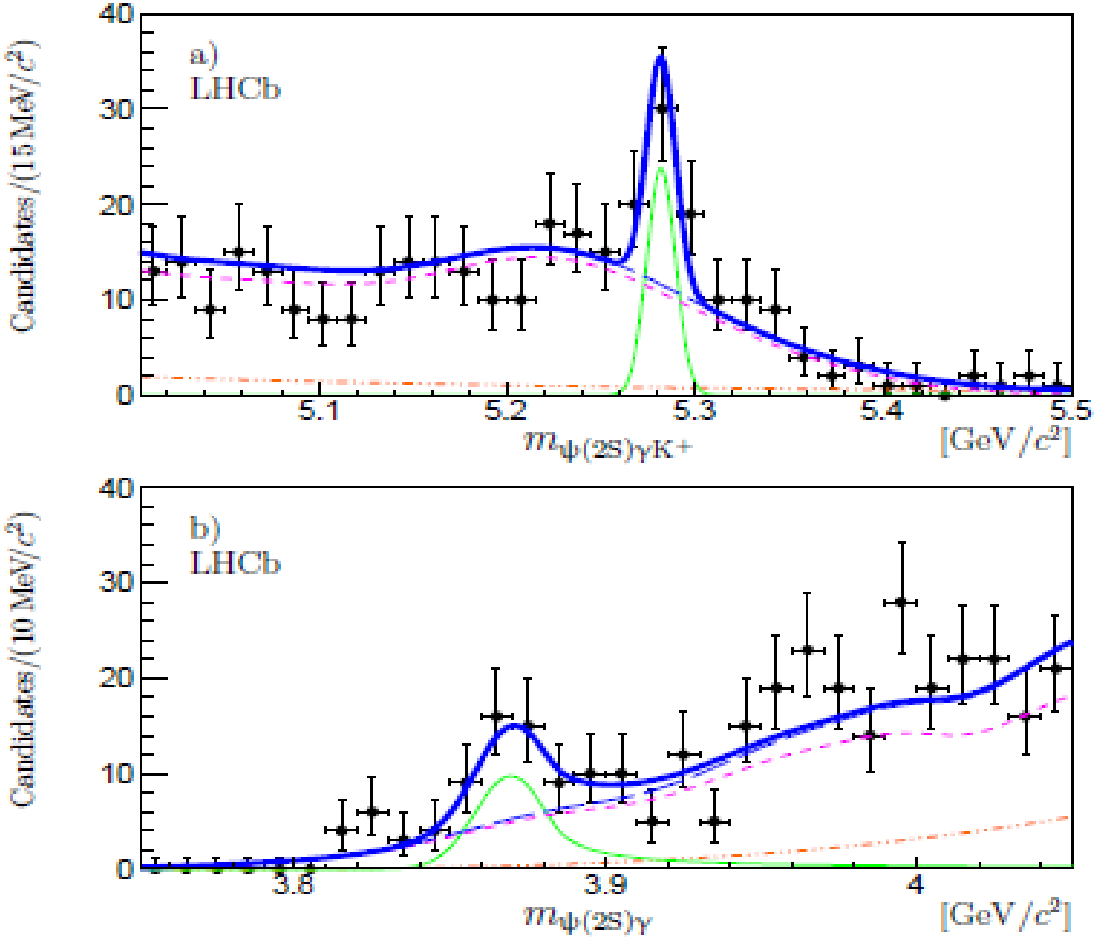


Figure 2: a) Distribution of the $\psi(2S)\gamma K^+$ invariant mass with fit projection overlaid, restricted to those candidates with $\psi(2S)\gamma$ invariant mass within $\pm 3\sigma$ from the X(3872) peak position. b) Distribution of the $\psi(2S)\gamma$ invariant mass with fit projection overlaid, restricted to those candidates with $\psi(2S)\gamma K^+$ invariant mass within $\pm 3\sigma$ from the B^+ peak position. The total fit (thick solid blue) together with the signal (thin solid green) and background components (dash-dotted orange for the combinatorial, dashed magenta for the peaking component and long dashed blue for their sum) are shown.

Theoretical results for the ratio R

- Earlier molecule model: $R=(3\text{-}4)\times10^{-3}$ Swanson PLB'04
- Recent molecule: systematical study for long-distance and short-distance contributions in XEFT: Mehen & Springer PRD'11
- χ'_{c1} model: E1 transition rates
  $\Gamma(\chi_{c1}(2p)\to\psi(2s)\gamma)=(40\text{-}60)$ KeV >
  $\Gamma(\chi_{c1}(2p)\to\psi(1s)\gamma)$
  due to node structure in wave functions.
  Measured ratio R may be naturally understood.
- Li & Chao, PRD'09, Badalin et al., PRD'12, and many earlier potential model calculations for E1 transitions

Summary

- With NRQCD factorization, the hadronic production cross section of X(3872) is evaluated up to NLO in α_s in the mixing model:

- The CMS p_T distribution can be fitted very well with $\chi^2/2 = 0.26$.
- The obtained r_{2P} for χ'_{c1} is almost the same as r_{1P} for χ_{c1} [MWC'11], which suggests that the X(3872) be produced through its χ'_{c1} component at short distances.
- The outcomes of the fit explain the CDF total cross section very well, however, the predicted cross section for the LHCb widow is larger than the data by a factor of 2, which might due to the large uncertainties.

- By harmonizing the fit results with those in B decays, we get

$$k = Z_{c\bar{c}}\mathrm{Br}(X \to J/\psi\pi^+\pi^-) = 0.018 \pm 0.004, \qquad r = 0.20\text{–}0.26,$$

which could be important to understand the nature of X(3872).

- The cross section in the molecule model is also evaluated at NLO in α_s, which is disfavored by both the CMS and the CDF data.

Summary

- The large ratio of X(3872) decays to ψ(2S)ɣ to that of J/ψɣ may be understood in the mixing model via $\chi_{c1}^{'}$ decay .
- The large and nearly equal production rates in both charged and neutral B meson decays may be understood by χ_{c1}'production at short-distances.
- Further studies are needed in both the molecule model and mixing model to understand various puzzles about the nature of X(3872).

Thanks!

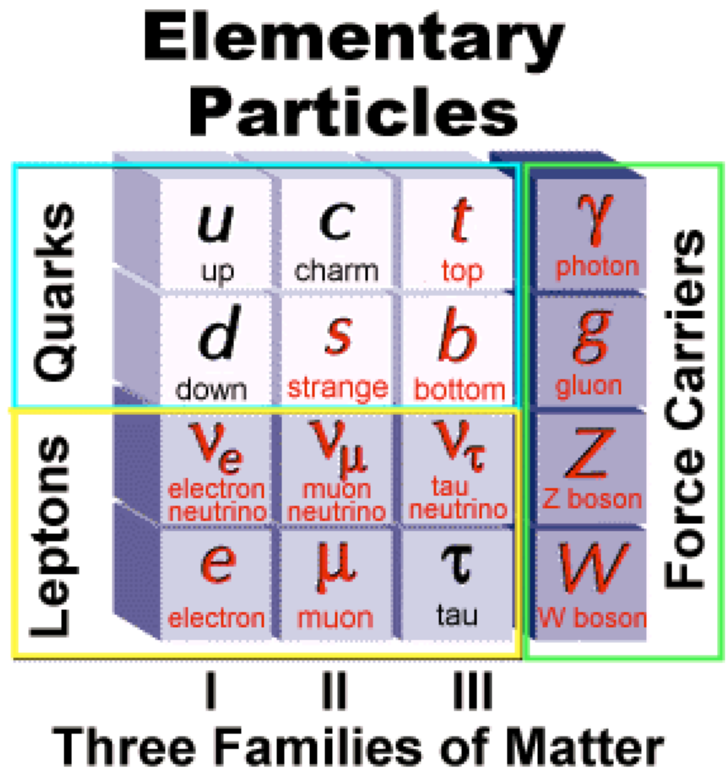
Heavy quarkonium: charmonium and bottomonium

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

Light quarks (u, d, s)

Λ_{QCD}

Heavy quarks (c, b, t)

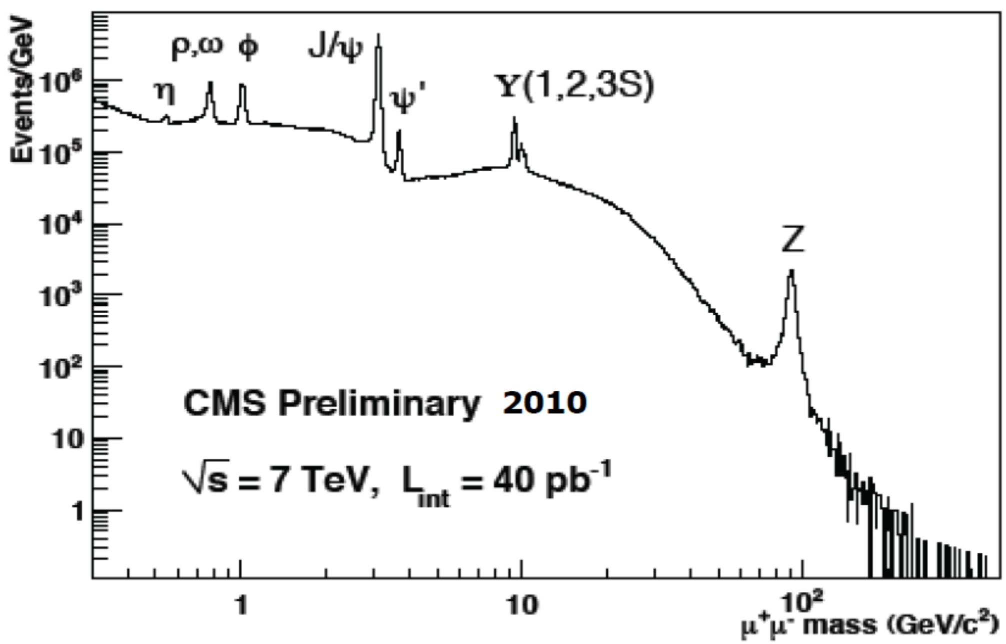


- Heavy quarkonium: composed of heavy quark and antiquark pair (J/Ψ, Ψ', χ_{cJ}, $\Upsilon(nS)$, χ_{bJ} …); nonrelativistic system: $v^2 << 1$, effective theories with different scales: m, mv, mv^2
- Heavy quark $m_Q >> \Lambda_{QCD}$, produced at short distances, pQCD applicable.

Study of heavy quarkonium production

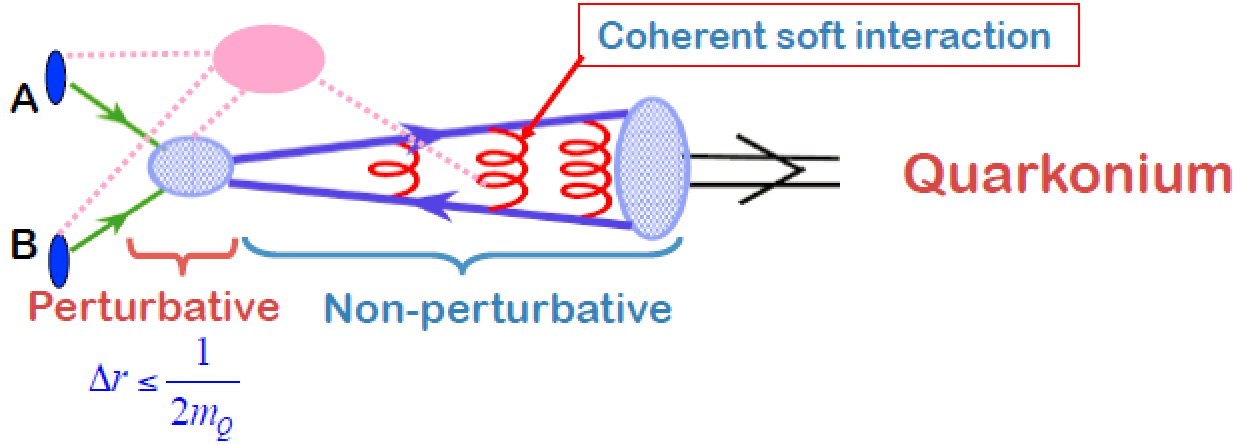
- Heavy quarkonia production: Provide an ideal laboratory to study pQCD and hadronization.

- Lots of heavy quarkonia (J/Ψ, Ψ’, χ_{cJ}, ϒ(nS), and even charmonium-like states X(3872) observed at LHC.



Factorization and hadronization

- Short distance and long distance parts. Hadronization followed by production of an off-shell heavy quark pair.



- ➢ Approximation: on-shell pair + hadronization.
  - ◆ Different assumptions/treatments on how the heavy quark pair becomes a heavy quarkonium: different factorization models.

$$\sigma_{AB\to H+X} = \sum_n \int_n d\Gamma_{(Q\bar{Q})_n} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{(Q\bar{Q})_n}}\right] F_{(Q\bar{Q})_n\to H}(p_Q, p_{\bar{Q}}, P_H)$$

NRQCD – factorization

$$d\sigma_{\psi} = \sum_{i,j,n} \int \underbrace{dx_1 dx_2 \, G_{i/A} G_{j/B}}_{\Lambda_{QCD}} \times \underbrace{\hat{\sigma}[ij \to c\bar{c}[n] + X]}_{m_c} \times \underbrace{\langle O_n^{\psi} \rangle}_{m_c v}$$

Parton distribution function
Long distance ($\sim 1/\Lambda_{QCD}$)
CTEQ6L1, CTEQ6M

Hadronization (LDMEs)
Long distance ($\sim 1/(m_c v)$)
input from experiments needed.

Production of heavy quark pair
Short distance ($\sim 1/m_c$)
perturbative calculable.

Widely used factorization methods

Since November revolution: Discovery of J/Ψ in 1974

- Color-singlet model (CSM): 1975 –
  - The pair has the same quantum numbers as the quarkonium
  - Effectively no free parameter.
- Color evaporation model (CEM): 1977 –
  - All pairs with mass less than open flavor heavy meson threshold;
  - One parameter per quarkonium state.
- NRQCD approach: 1986 –
  - Pairs can be produced in both color-singlet and color-octet states with various probabilities
  - Infinite parameters – organized in power of v .

Einhorn, Ellis, PRL 1975
Chang, NPB 1980
Berger, Jones, PRD 1981 …..

Fritsch, PLB 1977
Halzen, PLB 1977 ……

Caswell, Lepage, PRD 1986
Bodwin, Braaten, Lepage, PRD 1992

Heavy quarkonium production at hadron colliders

CSM – Ψ’ puzzle

- Twenty year ago, CDF collaboration found a surprisingly large production rate of Ψ’ at high p_T.
- The yield is larger than the theoretic prediction by a factor of 30, even though the fragmentation contribution is included.

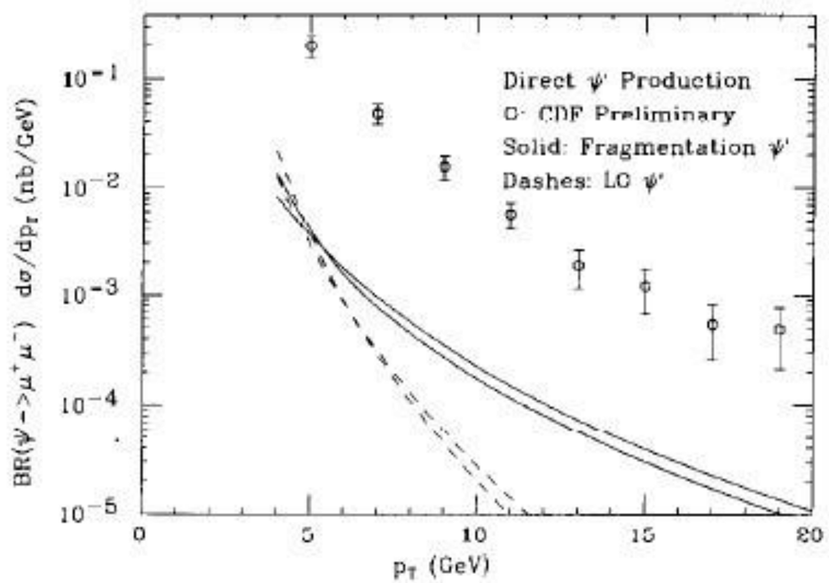


Fig. 4. Preliminary CDF data for prompt ψ′ production (O) compared with theoretical predictions of the total fragmentation contribution (solid curves) and the total leading-order contribution (dashed curves).

Braaten, Doncheski, Fleming, Mangano, PLB 1994

CSM – NLO Calculation

- Differential cross section is enhanced by 2 orders relative to LO CS result at high p_T. Still much smaller than data.
- Polarization is changed from being transversely polarized to

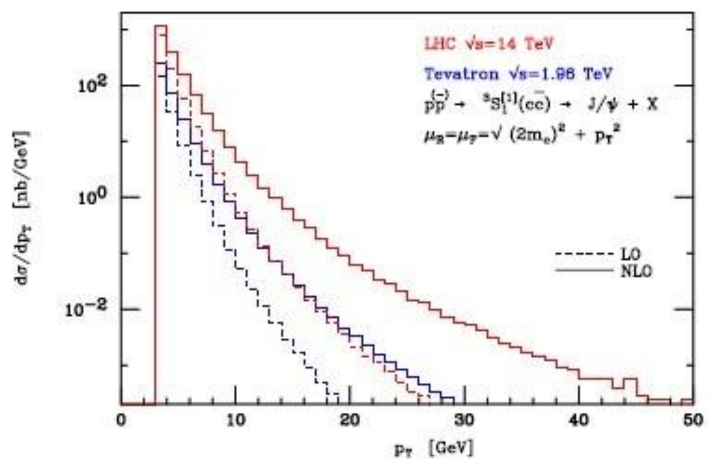
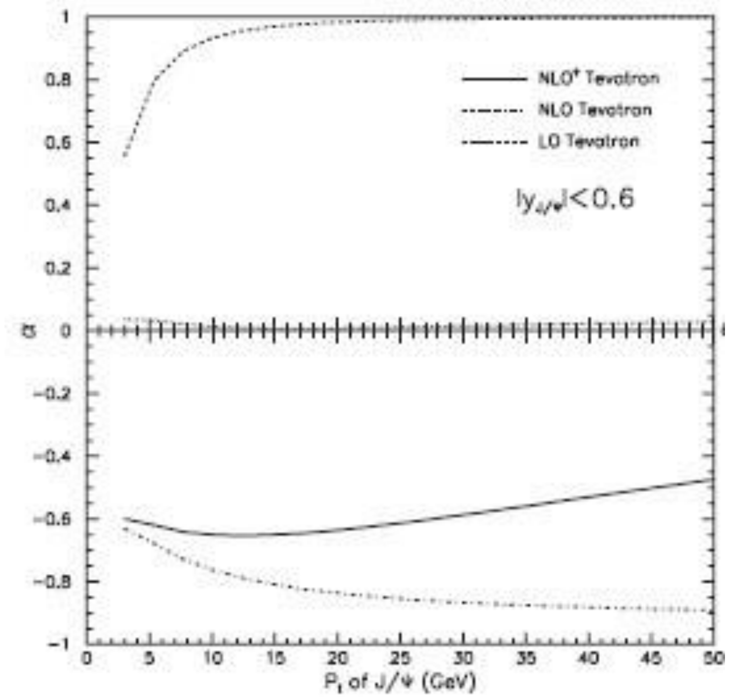


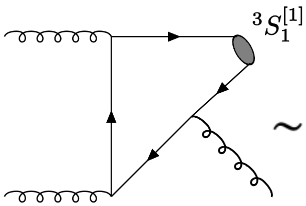
FIG. 5 (color online). Differential cross sections for direct J/ψ production via a ${}^3S_1^{[1]}$ intermediate state, at the Tevatron (lower histograms) and LHC (upper histograms), at LO (dashed line) and NLO (solid line). $p_T^{J/\psi} > 3$ GeV and $|y^{J/\psi}| < 3$. Details on the input parameters are given in the text.

Campbell, Maltoni, Tramontano, PRL 2007

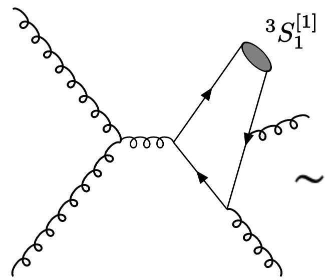


Gong, Wang, PRL 2008

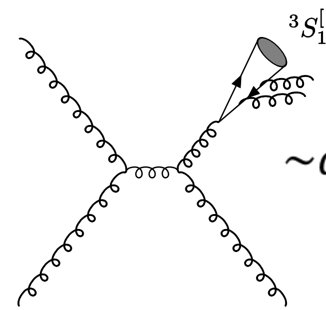
- At large p_T, p_T enhancement is more important than α_s suppression;



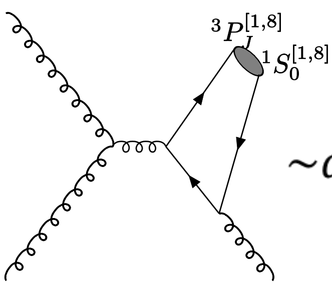
$$\sim\alpha_s^3\,\frac{m_Q^4}{p_T^8}$$



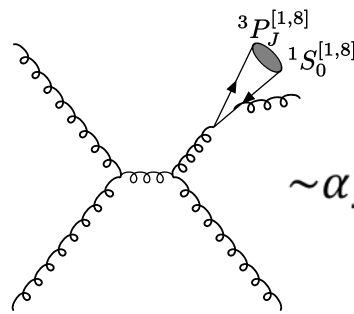
$$\sim\alpha_s^4\,\frac{m_Q^2}{p_T^6}$$



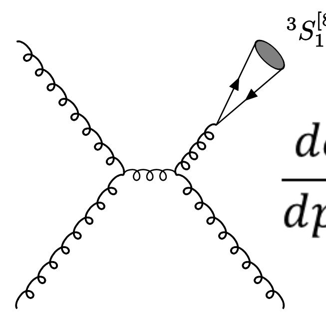
$$\sim\alpha_s^5\,\frac{1}{p_T^4}$$



$$\sim\alpha_s^3\,\frac{m_Q^2}{p_T^6}$$



$$\sim\alpha_s^4\,\frac{1}{p_T^4}$$



$$\frac{d\sigma}{dp_T^2}\sim\alpha_s^3\,\frac{1}{p_T^4}$$

Importance of complete NLO calculation

- One can conclude nothing definitely until the p_T^{-4} behavior of all channels are opened.
- NNLO contributions for $^3S_1^{[1]}$ may be safely ignored. (Ma, Wang, Chao, PRD 2011)

States	Order where p_T^{-4} present
$^3S_1^{[1]}$	NNLO
$^3S_1^{[8]}$	LO
$^1S_0^{[1,8]}$	NLO
$^3P_J^{[1,8]}$	NLO

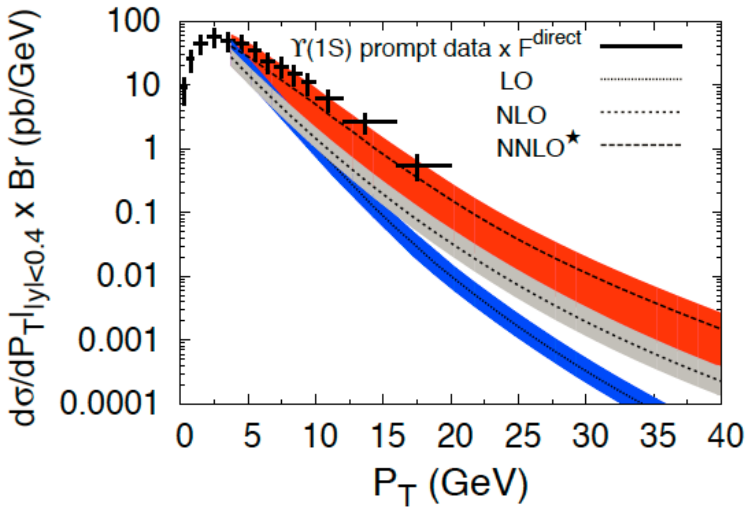
A complete NLO calculation to heavy quarkonia production is essential to understand the production mechanism.

- NLO correction for P-wave channel is needed!

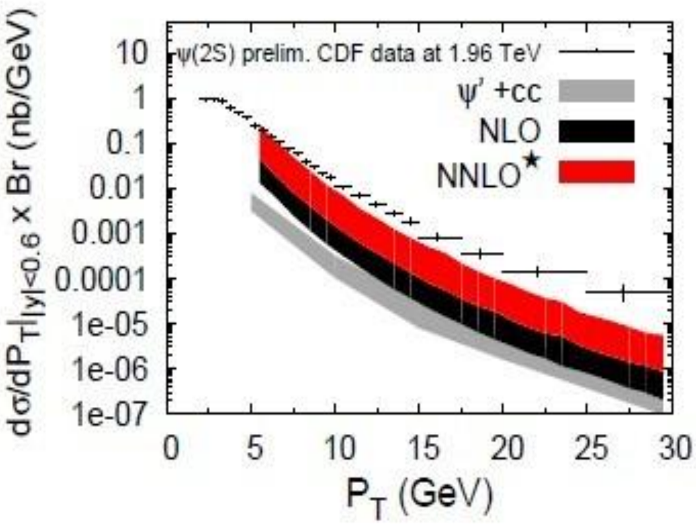
- Typical NLO calculation: a small correction, improve the precision of theoretic prediction and reduce uncertainties induced by renormalization scale and factorization scale.
- NLO calculation here: NOT A CORRECTION! But provide the main contribution for some channels which are suppressed by kinematics at LO.

CSM –NNLO* calculation

- NNLO correction to CS channel is estimated by calculating only tree level diagrams (NNLO*). An infrared cutoff s_{ij}^{min} is imposed to control soft and collinear divergences.



Artoisenet, Campbell, Lansberg, Maltoni, Tramontano, PRL 2008

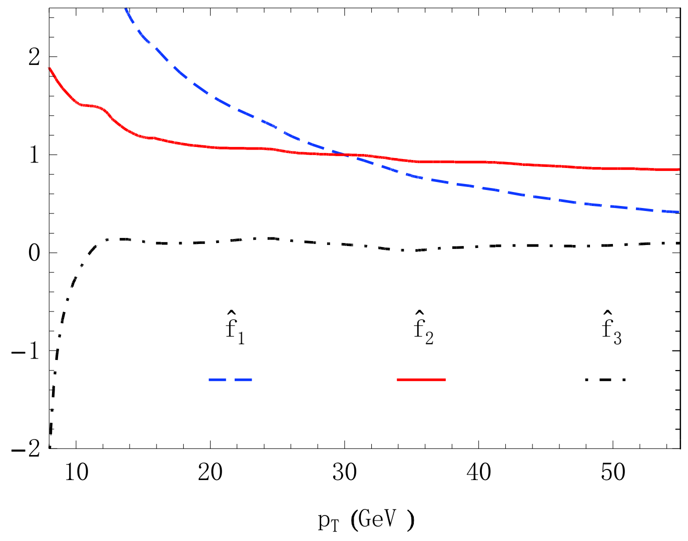


Lansberg, EPJC 2009

- Large corrections. Almost reach the data.

CSM – Problem

- Theoretically:
  - IR divergence in NLO correction for P-wave.
- Phenomenology: CSM cannot explain experiment data even including NNLO contribution (Ma, Wang, Chao, PRD 2011)
  - The only new behavior is the gluon fragmentation, which scaling as p_T^{-4}. Other contributions at this order is suppressed by α_s relative to NLO.
  - The fragmentation contribution has been calculated by E. Braaten et al. , and they are as small as 1/30 of the experiment data.
  - NNLO* is dominated by double logarithm, which will be canceled by loop corrections. Thus NNLO* method may overestimate the CSM contribution.



$$R^\star = d\sigma_{NNLO^\star}/d\sigma_{NLO}$$

$$\hat{f}_1 = \frac{R^\star}{p_T^2}\Big|_{s_{ij}^{min}=0.5m_b^2}$$

$$\hat{f}_2 = \frac{R^\star}{\log^2(p_T^2/s_{ij}^{min})}\Big|_{s_{ij}^{min}=0.5m_b^2}$$

$$\hat{f}_3 = 1 - \frac{R^\star/\log^2(p_T^2/s_{ij}^{min})\,|_{s_{ij}^{min}=2m_b^2}}{R^\star/\log^2(p_T^2/s_{ij}^{min})\,|_{s_{ij}^{min}=0.5m_b^2}}$$

CSM – Convergence of v^2 expansion

- To further confirm that the CSM is not enough to explain data, it is needed to study the convergence of v^2 expansion.

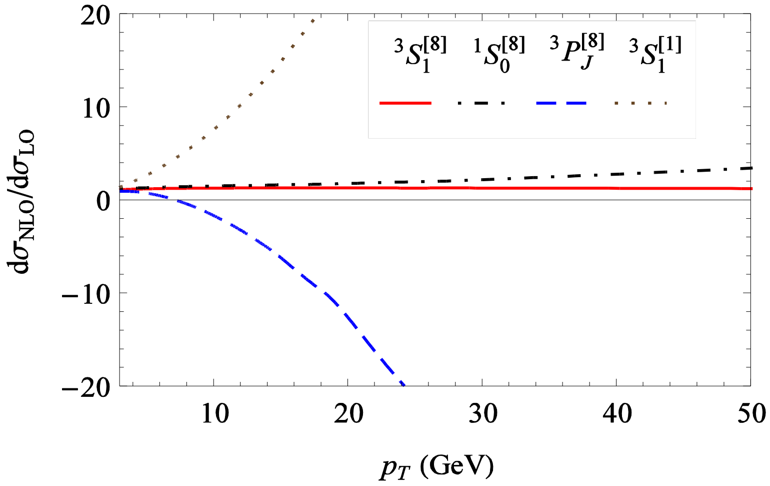
- Up to relative-order-v^4 correction for gluon fragmentation into J/Ψ in the CS channel has been done by Bodwin, Kim, Lee, 1208.5301. The finite term of order-v^4 contribution was found to be not important numerically. That is, p_T^{-4} contribution of CSM is not important.

- v^2 correction for p_T^{-6} contribution of CSM is studied by Chao, Li, Ma (In progress) . The convergence of v^2 expansion is found to be very good. p_T^{-6} contribution of CSM is less than one-tenth of experiment data when p_T>10 GeV.

- Considering also that other higher power contributions are not important at large p_T, CS channel contributions are neglectable when p_T>10GeV.

Complete NLO correction for Ψ – yield

- Two groups calculated it independently: Ma, Wang, Chao (MWC) and Butensckön, Kniehl (BK).
- The results of the two groups for the short-distance coefficients agree.



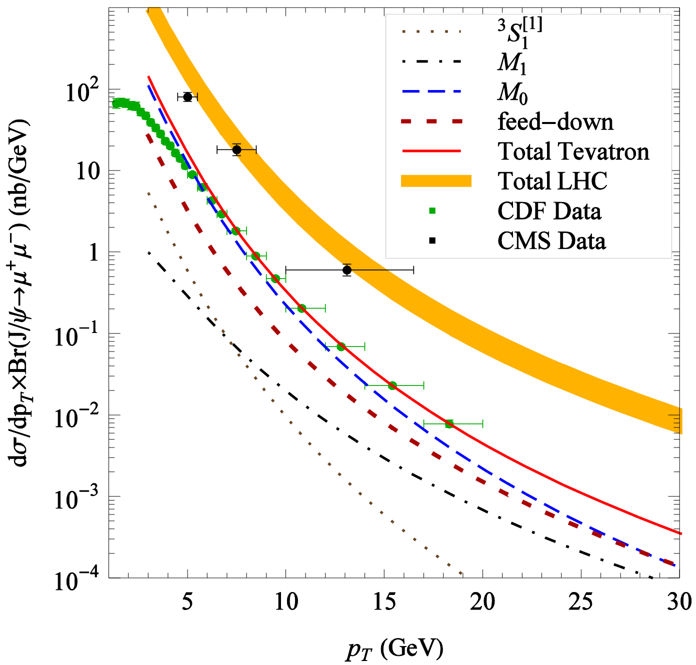
➢ Methods of fit NRQCD LDMEs are different:

◆ MWC: select only data that can be safely described by perturbation theory to fit LDMEs, although only some linear combinations of LDMEs can be determined.

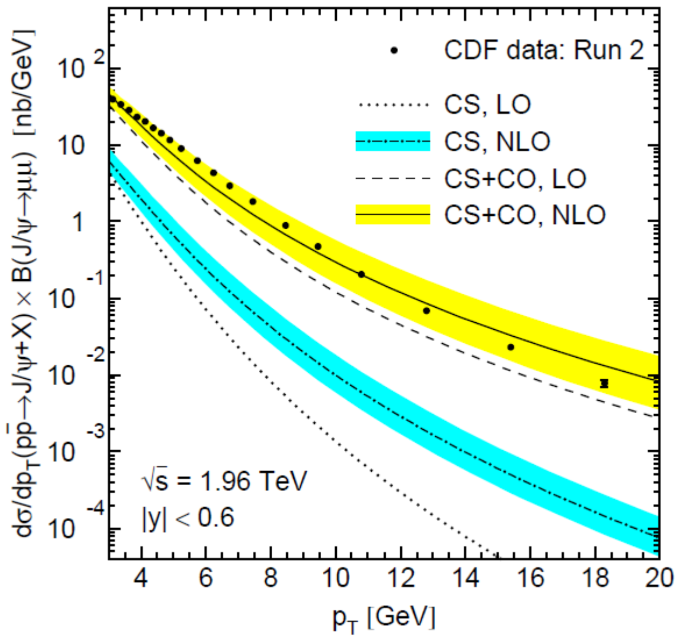
◆ BK: fit as many as possible data to determine all three CO LDMEs.

Complete NLO correction for Ψ – yield

- MWC: agree with data only for p_T>7GeV, but the agreement is very good;
- BK: all data for p_T>3GeV can be described within large errors.



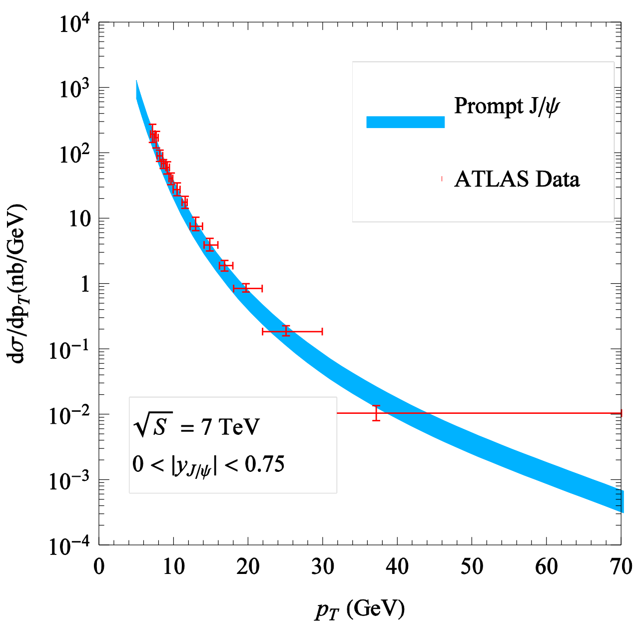
MWC, PRL 2011



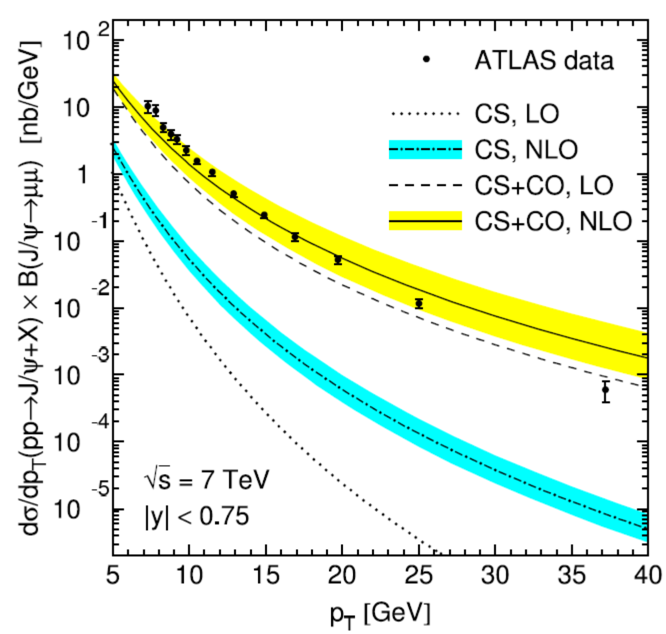
BK, PRL 2011

- MWC: agree with data only for p_T>7GeV, but the agreement is very good (up to 40-70 GeV);
- BK: data for p_T>3GeV can be described within large errors.

Confront with Large p_T data



MWC

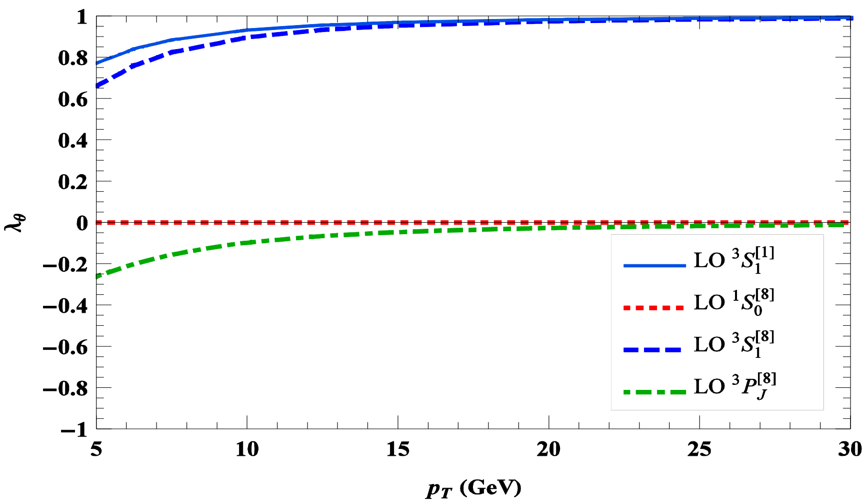


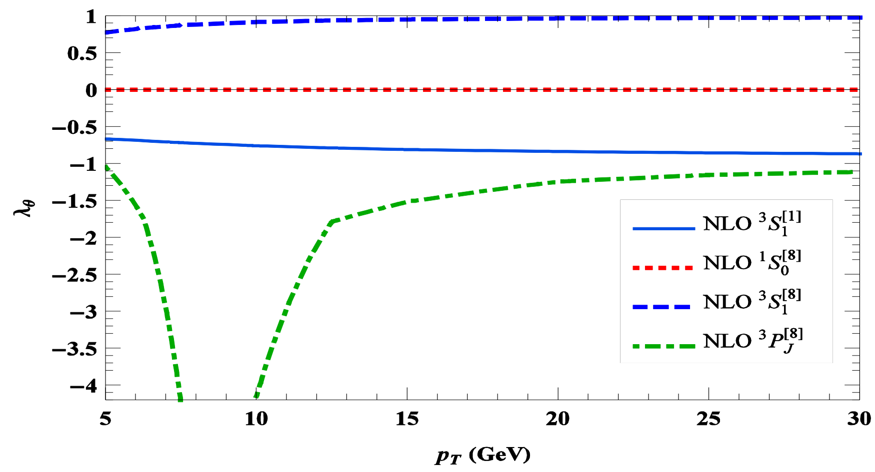
BK

Complete NLO correction for Ψ – polarization

$$\lambda_\theta = \frac{d\hat{\sigma}_T - 2d\hat{\sigma}_L}{d\hat{\sigma}_T + 2d\hat{\sigma}_L}$$

- For P-wave channel $\lambda_\theta<1$, which results from short distance coefficient behavior: $d\sigma_T<0$ and $d\sigma_L>0$;
- Negative transverse component of $^3P_J^{[8]}$ channel may cancel the transverse component of $^3S_1^{[8]}$ channel, leading to mainly unporalarized J/Ψ.

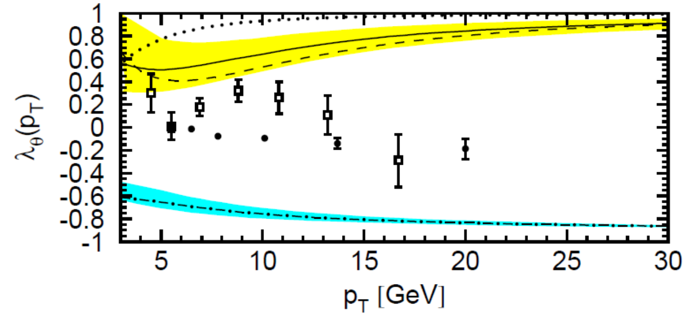




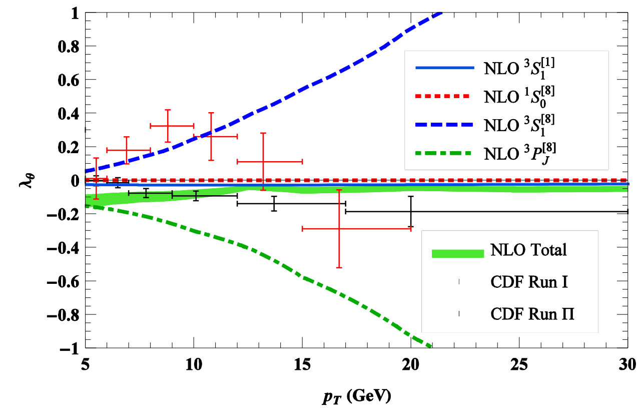
Polarization predicted by three groups

1. Butensckön and Kniehl: direct; LDMEs: global fit of pp, ep, γγ and e^+e^- data; conflict with CDF data.
2. Chao, Ma, Shao, Wang and Zhang: direct; LDMEs: fit yield of CDF and LHC data (especially large p_T data); consistent with CDF data.
3. Gong, Wan, Wang and Zhang: prompt; LDMEs: fit yield of CDF and LHCb; agree with Run-I data (except two points), but conflict with Run-II data.

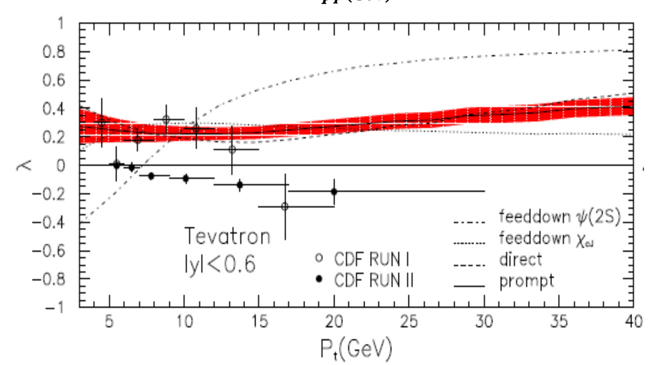
J/Ψ



BK



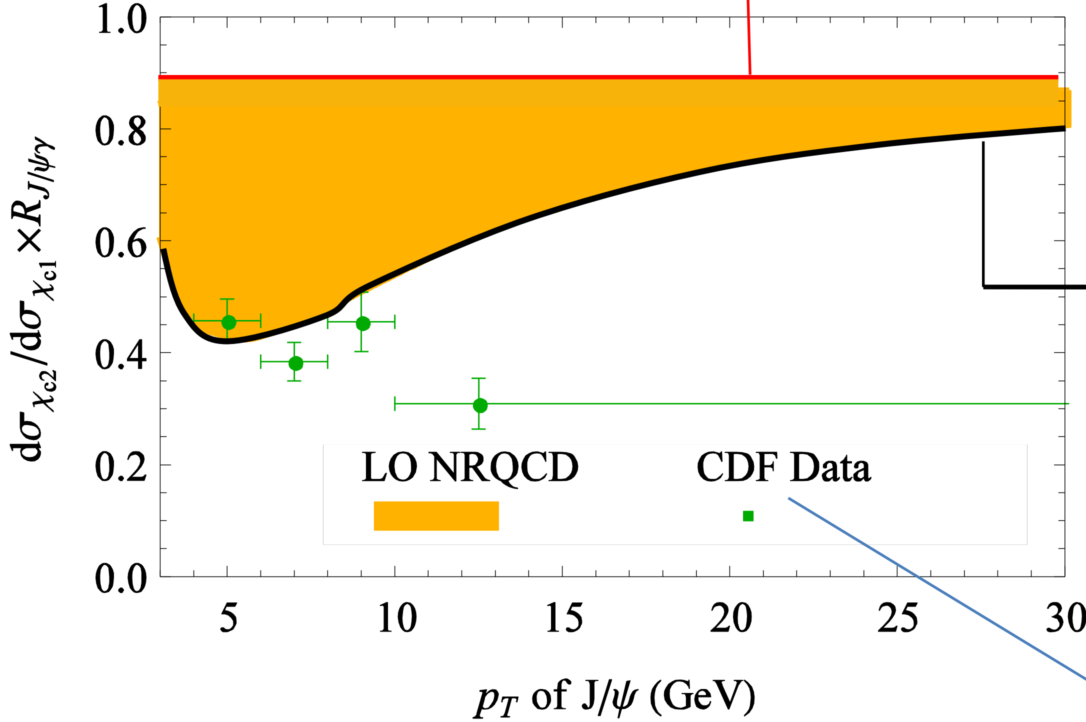
CMSWZ



GWWZ

- Prompt polarization by GWWZ is not much different from their direct polarization.
- For direct polarization, the only difference between the three groups is the choice of LDMEs.
- **How to fit LDMEs ???**
- **Polarization data from LHC for larger pT**

χ_{cJ} ratio puzzle



r=10 and CEM

r=0.1

$$r = \frac{\langle O^{\chi_{c0}}({}^3S_1^{[8]})\rangle}{\langle O^{\chi_{c0}}({}^3P_0^{[1]})\rangle / m_c^2}\Big|_{\overline{MS},\mu_\Lambda=m_c}$$

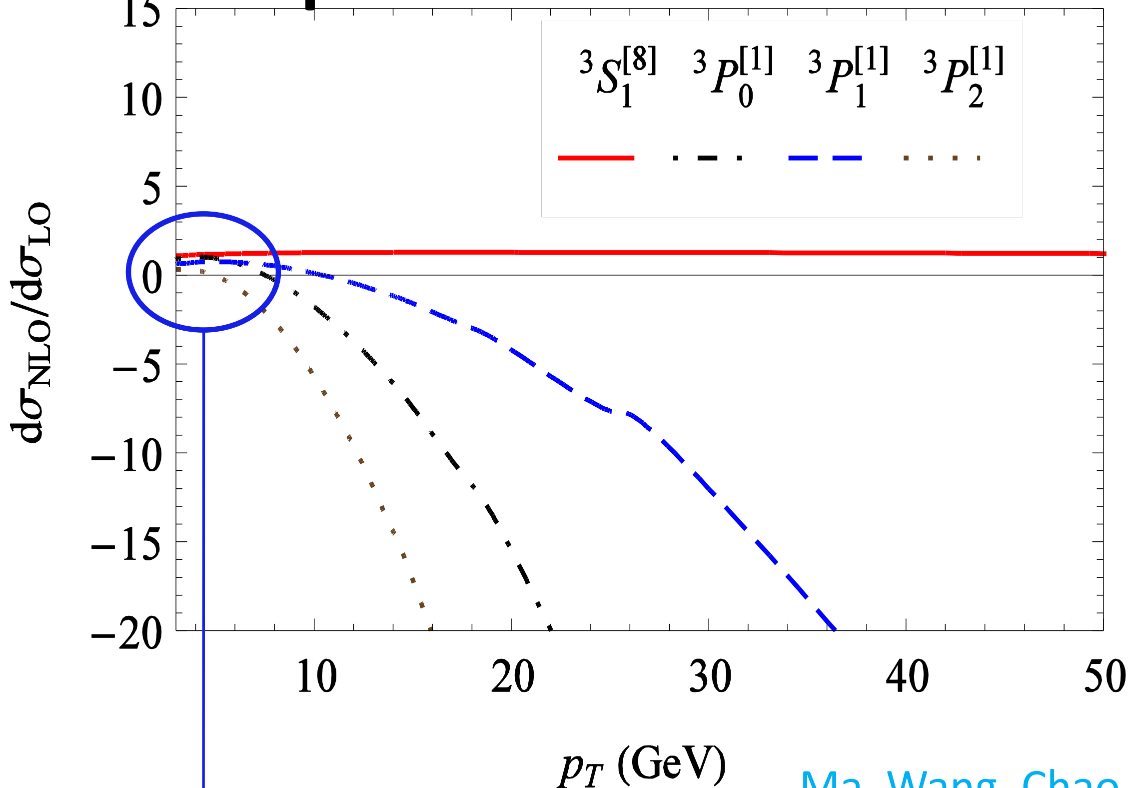
CDF Collaboration, PRL 2007

•LO NRQCD prediction, dominated by CO channel at high p_T, is far away from the experiment data even though $0.1<r<10$ ($r \approx 1$ based on NRQCD).

$$\frac{d\sigma_{\chi_{c2}}}{d\sigma_{\chi_{c1}}} \xrightarrow{p_T \gg m_c} \frac{5}{3}$$

•CEM is even worse: $d\sigma_{\chi_{c2}} / d\sigma_{\chi_{c1}} \equiv 5/3$

Complete NLO correction for χ_{cJ} (1)



Ma, Wang, Chao, PRD(R) 2011

K factor of each channel.

- Large but negative corrections are found.
- CS channel of χ_{c2} declines much faster than χ_{c1}.

Different behavior from CO channel.

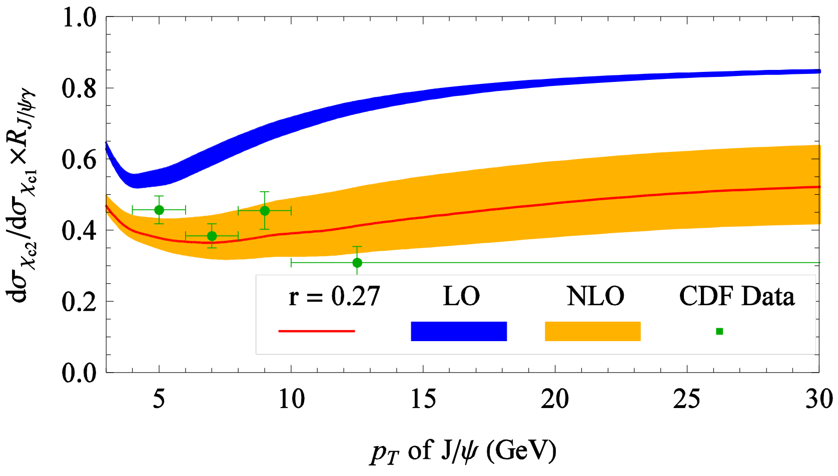
Subtraction scheme and NRQCD renormalization scale dependent.

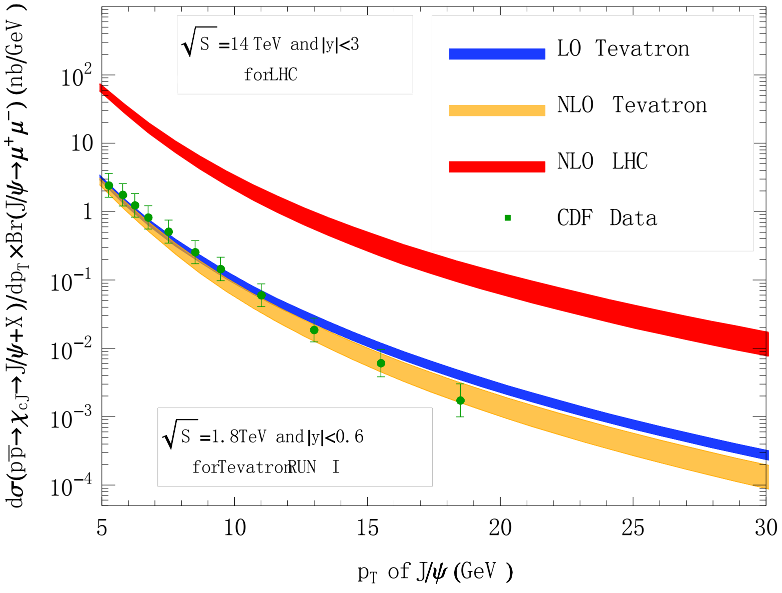
Large corrections originate from $p_T/(2m_c)$

Complete NLO correction for χ_{cJ} (2)

- Ratio $d\sigma_{\chi_{c2}}/ d\sigma_{\chi_{c1}}$ can be explained in NLO;
- Differential cross section is also improved.

Ma, Wang, Chao, PRD(R) 2011





Complete NLO

- Ratio $d\sigma_{\chi_{c2}} / d\sigma_{\chi_{c1}}$: good agreement with LHCb and CMS data;
- CMS data further confirm that $d\sigma_{\chi_{c2}}/d\sigma_{\chi_{c1}} \neq 5/3$ even p_T is very large.